The Effect of Magnetic Field on the Position of HTS Leads and the Cooler in the Services Tower of the MICE Focusing Magnet

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***Abstract*— The MICE focusing solenoids have three 4 K coolers (two for the superconducting magnet and one for the liquid absorber) and four HTS leads that feed the current to the focusing coils. The focusing solenoids produce large radial external fields when they operate with the polarity of the two coils in opposition (the gradient or flip mode). When the MICE focusing coils operate at the same polarity (the solenoid or non-flip mode), the fields are much smaller and parallel to the axis of the solenoid. The worst-case magnetic field affects the selection of the cooler and the HTS leads. This magnetic field can also determine the height of the service towers that house the three coolers and the four HTS leads. This paper shows the criteria used for Cooler selection, HTS lead selection, and the position of both the cooler and leads with respect to the solenoid axis of rotation.**

***Index Terms*—4 K Cooler, HTS Leads, Service Tower**

I. Introduction

THE muon ionization cooling experiment (MICE) is an experiment that is designed to show that the emittance of muons can be reduced (muon cooling) in a short cooling channel [1]. Because muons have a short life (~2.1 μs at rest), conventional beam cooling methods cannot be used. Muon ionization cooling occurs when a muon passes through a low z material such as hydrogen or lithium hydride.

In MICE the emittance of muons is reduced by reducing the momentum of the muons (both transverse and longitudinal directions) in an absorber and then reaccelerating the muons to restore the longitudinal momentum. If muon cooling is achieved, there will be a net reduction in the muon transverse momentum at the end of the cooling channel. The muon cooling is essential if muons are to be accelerated to high energies for a neutrino factory or a muon collider.

The place where the reduction of muon momentum occurs is the absorber focus coil (AFC) module [2]. The AFC module consists of a two-coil superconducting magnet that surrounds an absorber [3]. The AFC module is designed so that either a liquid (hydrogen or helium) or solid absorber can be used [4].

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II. The AFC Module and its Magnet

This report talks about the effect of an external magnetic field on the AFC magnets and their coolers. The 12-meter long MICE cooling channel has eighteen superconducting coils that operate without an iron shield. The fields inside of the MICE cooling channel vary as one moves along the magnet axis. The on axis field depends on the function being performed in that part of the channel and on the experiment operating-mode. The magnitude of the field along the magnet axis can be as high as 5 T depending on the experiment operating-mode and muon momentum. The direction of the magnetic field on axis can vary depending on the experiment operating-mode.

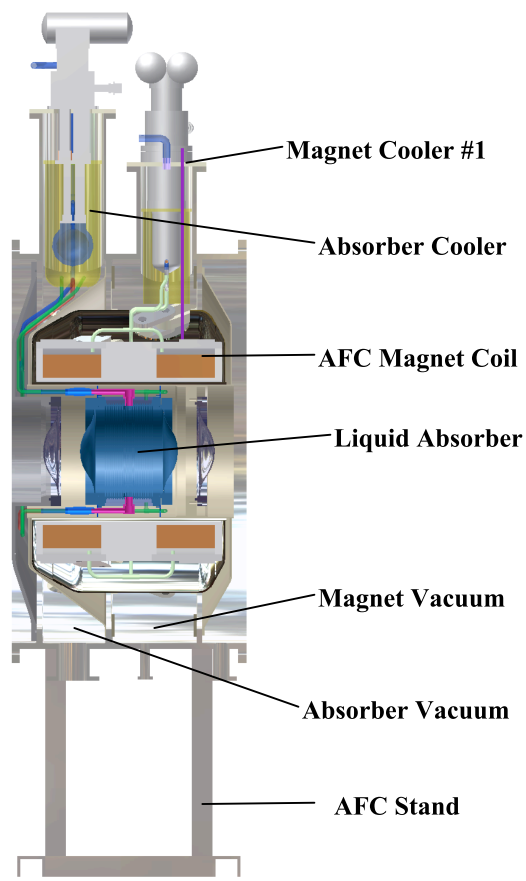

Fig. 1 A cross-section view of the MICE AFC Module showing the Magnet Coils, the Liquid Absorber, the Cryostat Vacuum Vessel and the Coolers.

A cross-section of the AFC module is shown in Fig. 1. The AFC magnet consists of two coils, each with its own set of leads. MICE is designed to operate in two different general modes, the flip mode and the non-flip mode. The operating mode for the MICE channel is set by the polarity of the two coils in each AFC module.

When the AFC magnet is in the flip mode, the two focusing coils are connected in series so that the field polarity is reversed. In the flip mode, the magnetic field reverses as one goes down the axis of the magnet. The magnetic field is zero in the center of the AFC module. The polarity of the magnets on either side of the AFC magnet is the same as the nearest AFC coil. The MICE on-axis field changes sign within an AFC magnet that is in the flip mode.

When the AFC magnet is in the non-flip mode, the two focusing coils are hooked up in series so that the two coils have the same field polarity. In the non-flip mode, the sign of the magnetic field does not change as one goes down the magnet axis. When the AFC magnet is in the non-flip mode, there is no zero field region within the bore of the AFC module. In the non-flip mode the polarity of the magnets on either side of the AFC magnet is the same as the AFC magnet.

Table 1 shows the basic parameters of the AFC magnet. The currents, current densities, stored energy and external field are shown for the AFC magnet being operated at the highest currents, which corresponds to a muon average momentum of 240 MeV/c and a beam beta at the center of the AFC magnet of 420 mm. The current related data is given for both the flip and the non-flip cases.

TABLE I. THE BASIC OPERATING PARAMETERS OF THE MICE FOCUSING MAGNET IN THE FLIP AND NON-FLIP MODES

Parameter	Non-flip	Flip
Warm Bore Radius (mm)	235	
Outer Cryostat Radius (mm)	700	
Coil Inner Radius (mm)	263	
Coil Thickness (mm)	84	
Number of Conductor Layers	76	
Number of Turns per Layer	127	
Magnet J (A mm^{-2})*	72.0	138.2
Magnet Current (A)*	130.5	250.7
Magnet Self Inductance (H)	137.4	98.6
Peak Induction in Coil (T)*	5.04	7.67
Magnet Stored Energy (MJ)*	1.17	3.10
4.2 K Temp. Margin (K)*	~2.0	~0.6
External B at R = 0.7 m (T)*	0.12	~0.66
Direction of Field Lines	Axial	Radial
Inter-coil Z Force (MN)*	-0.56	3.53

* Worst case currents based on p = 240 MeV/c and β = 420 mm

In the AFC magnet, the outer vacuum vessel radius is about 2.7 times larger than the coil inner radius. The HTS leads and the second stage of the magnet and absorber coolers must be located in a chimney that is at a larger radius than the outer cryostat radius. The exact location of the coolers and the HTS leads is determined by the external magnetic field.

III. MAGNETIC FIELD OUTSIDE OF THE AFC MAGNET

The field outside of the MICE magnets varies with the magnet type, the operating mode, and the radial distance from the channel axis. When one looks at MICE as a whole in its final stage, one sees that MICE has a magnetic moment of zero in the flip mode. In the non-flip mode the magnetic moment of MICE is never zero. A zero net magnetic moment means that the magnetic field will fall away rapidly at distances that are greater than the length of the MICE channel. Zero net magnetic moment only helps with the shielding of of the whole of MICE from the MICE control room, which is a large distance from the MICE magnet axis. The stray magnetic fields outside of individual magnets are higher in the flip mode than in the non-flip mode, because in general the magnet currents are higher. As a result, one must design the MICE magnet system for the worst-case (240 MeV/c) flip-mode stray field. The highest field at the HTS leads and the cooler will occur in the AFC magnet when the muon momentum is 240 MeV/c. A field map outside of the AFC magnet cryostat is shown in Fig. 2.

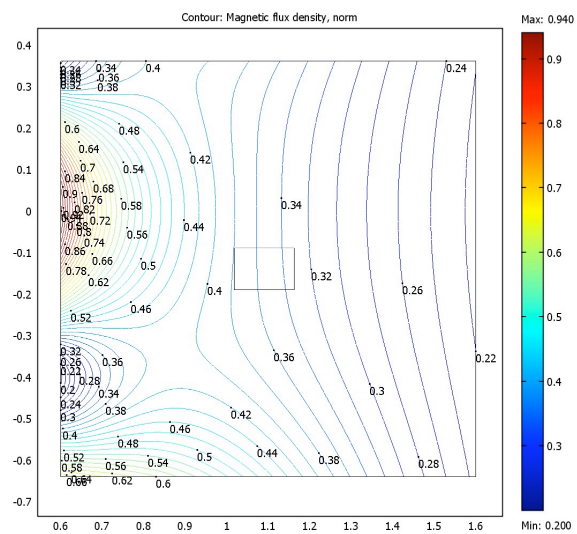

Fig. 2. A Contour Plot of the Worst-case Magnetic Induction from R = 0.6 m to R = 1.7 m and from Z = -0.6 m to +0.4 m. The square in the contour plot indicates the location of the HTS leads and the magnet cooler second stage.

From Fig. 2, it is clear that the magnetic induction outside of the AFC cryostat vacuum vessel is above 0.4 T even at a radius of ~1 meter from the axis of the magnet. The AFC magnet cryostat extends from z = - 0.4 m to z = +0.4 m. There is no region on the surface of the cylindrical portion of the cryostat (at R = 0.7 m) where the magnetic field is less than 0.36 T, so the only real solution is moving the second stage of the cooler to a radius where the magnetic field does not cause a problem for the HTS leads and the magnet coolers.

IV. THE HTS LEAD AND MAGNETIC FIELD

External magnetic field is a critical selection criterion for the type of HTS lead to be used in the any magnet [5]. All of the MICE magnets are cooled using 4.2 K coolers. All of the MICE magnets use one or more pairs of HTS leads between the cooler first and second stages.

It is expected that leads fabricated from multifilament BSCCO tape will be used for all of the MICE magnets. The best kinds of leads to use in magnets where the external stray field is a problem are leads with two preferred field directions. On an axial symmetric solenoid, the two preferred field directions for the HTS leads should be on a radial line from the magnet axis and on a line in the z direction that is parallel to the magnet axis. There should be no transverse field.

A cross-section of the tape used in a typical BSCCO tape lead is shown in Fig. 3. In Fig. 3 the preferred field direction is parallel to the flat face of the BSCCO tape. The non-preferred field direction (bad field direction) is perpendicular to the flat face of the BSCCO tape. Fig. 4 shows the parallel (preferred) and perpendicular (non-preferred) field direction for a typical commercial HTS lead made from BSCCO tape.

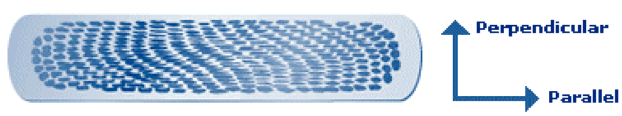

Fig. 3. A Cross-section of a BSCCO-2223 Tape used in Commercial HTS Leads that are designed to Operate in an External Magnetic Field. Note: the preferred (good) field direction is parallel to the flat face of the lead. The non-preferred (bad) field direction is perpendicular to the flat face.

Fig. 4. A 300 mm Long Commercial HTS lead showing Field Directions Parallel (preferred) and Perpendicular (not preferred) to the Flat Face of the BSCCO Tape that is inside the HTS Lead.

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The nominal design current for most commercial HTS leads is set for the self-field in the lead (the magnetic field generated in the HTS conductor due to the current flowing in the lead) at a temperature of 64 K.

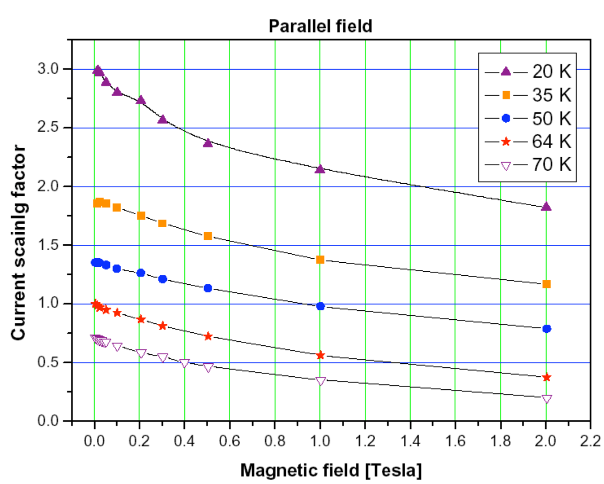

Fig. 5 The normalized Current in a Typical BSCCO-2223 Flat Tape HTS Current Lead as Function of Magnetic Field and Temperature with the Magnetic Field Parallel to the Flat Face of the HTS Tape.

Fig. 5 shows the normalized current for a commercial BSCCO lead in an external field that is parallel to the flat face of the HTS tape. Fig. 6 shows the normalized current for a commercial BSCCO lead in an external field that is perpendicular to the flat face of the HTS conductor. The normalized HTS lead current is one at 64 K when there is no external field [6].

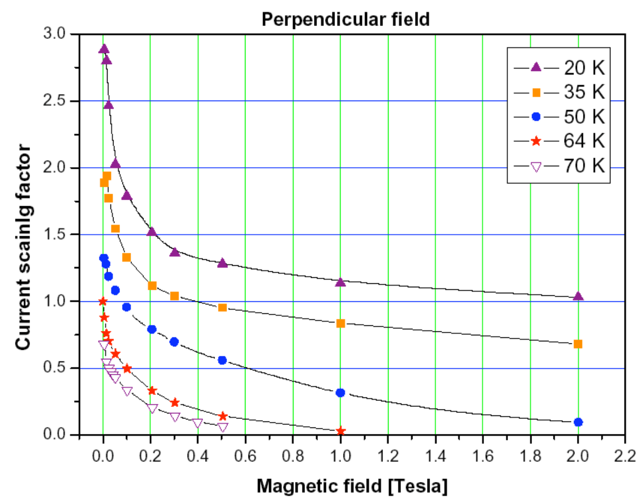

Fig. 6 The normalized Current in a Typical BSCCO-2223 Flat Tape HTS Current Lead as Function of Magnetic Field and Temperature with the Magnetic Field Perpendicular to the Flat Face of the HTS Tape.

In general, one would like to be able to run the lead at temperatures above 64 K in the event of a cooler failure or power outage. As a result, one should set the maximum HTS lead design current as high as possible above 70 K.

From Fig. 5 and Fig. 6, several things are clear. First, when there is an external field, one wants an HTS lead that has two preferred field directions. Second, one wants to avoid subjecting the conductor in the lead to any field that is in the non-preferred direction (perpendicular to tape surface). Third, the HTS conductor in the lead should have a high critical field. Fourth, one wants to run the first stage of the cooler at the lowest possible temperature. Running the first stage of the cooler at the lowest possible temperature means that the temperature margin at the top of the HTS leads will be maximized. The helps protect the HTS lead from quenching when the magnet discharges during a power failure [7]

V. Cooler Selection and Cooler Location

Cooler selection is an important part of the design of the magnet when the cooler must operate in a magnetic field [8]. There are two types of coolers that are commercially available for cooling the magnets in MICE. These are the Gifford McMahon (GM) coolers and the pulse tube (PT) coolers. Today, GM coolers are widely used for MRI magnets. GM coolers are preferred in any application where the cooler is not oriented so that the cold end is down. PT coolers must be oriented so that the pulse tubes are vertical with the cold end down. There is a serious degradation in PT cooler performance if they are not operated in this way. PT coolers are used when cooler vibration is a key issue, but this in not important for coolers operating on MICE. PT coolers require less maintenance than GM coolers.

The effect of magnetic field on the two types of coolers is very different. GM coolers are sensitive to magnetic field in the displacer motor, the drive crosshead, and in the cooler displacers. PT coolers are sensitive to magnetic field only in the motor that drives the rotary valve that produces the pulsation in the pulse tubes. The performance of the second-stage rare-earth regenerator degrades in a magnetic field above 1.5 T. This is not an issue in MICE for either type of cooler.

The drive motor in an RDK-415 GM cooler stalls when the induction at the motor is about 0.07 T. (The RDK415 cooler produces 1.5 W at 4.2 K on the second stage while producing 40 W at 55 K on the first stage using 50 Hz power.) When the motor stalls, the cooler no longer produces cooling. The crosshead can probably operate in a magnetic induction that is up to 0.2 T. Since the motor and the crosshead are in the same general location, the crosshead is not the issue in a GM cooler. Field perpendicular to the motion of the displacer causes the displacer to rub against its cylinder wall. As a result, the interval between maintenances will be shortened, because of the excessive wear in the displacers. The field perpendicular to the displacer tube should not be greater than 0.05 T. The field parallel to the axis of the displacer can be higher (perhaps as high as 0.15 T). Studies at Oxford [7] show that a GM cooler motor can be shielded for inductions of 0.1 T in any direction. When the induction is increased to 0.35 T, the induction within the motor varies from 0.18 to 0.27 T depending on the field direction. The probable upper induction limit for a shielded GM cooler motor is ~0.14 T

The drive motor for a Cryomech PT415 pulse tube cooler stalls at a magnetic induction above ~0.08 T. (The PT415 cooler produces 1.5 W at 4.2 K on the second stage while producing 40 W at 45 K on the first stage using 50 Hz power.) The motor can be shielded by replacing the aluminum motor and valve housing with one made from soft iron. Studies at Oxford [7] show that the motor for a PT415 cooler can be shielded for inductions up to 0.3 T in any direction. There is a concern about whether the motor iron shield will affect the quality of the magnetic field on the axis of the MICE cooling channel. If field errors in MICE are an issue, the cooler rotary valve assembly and ballast tanks can be moved to a location up to 1-meter from the cooler cold head.

A strong case can be made for the three coolers for the AFC module being pulse tube coolers, because the cooler motor can be shielded using iron in a field of 0.3 T, or the motor can be moved to a region with a magnetic induction less than 0.08 T.

VI. The Location of the AFC Coolers and Leads

The maximum AFC magnet lead current is about 250 A. If the cooler first-stage is at a radius of 1.2 m, the magnetic induction goes down to 0.33 T in the worst-case. At a radius of 1.2 m, a 500 A HTS lead can carry 250 A at about 73 K.

Keeping the top of the HTS leads cold while discharging the magnet during a power failure is a critical issue [8]. A rapid discharge system that discharges the AFC magnets in less than 3600 seconds is needed to protect the HTS leads in the magnet, during a power failure.

The rotary valve motor for a PT415 cooler is about 0.4 m above the cooler first-stage. At a radius of 1.6 m, the average magnetic induction at the cooler rotary valve motor is about 0.22 T. The cooler rotary valve can be shielded be replacing the aluminum valve and motor housing with a nickel-plated iron housing. There is no extra charge for this shielding. The minimum distance from the magnet axis to the top of the cooler will be ~1.75 meters. This minimum distance applies to all of the coolers used for the AFC module.

VII. Concluding Comments

The stray magnetic field generated by the AFC module superconducting solenoid determines the type of HTS leads used to supply the magnet with current. The type of cooler used to cool the AFC magnet and the liquid absorber is also determined by the presence of a magnetic field. Because the level of the magnetic field is an issue in MICE, the PT415 coolers will be used on the other MICE magnets [9]-[10].

The radial position of the cooler is determined by the magnetic field at the top of the HTS leads, which in turn determines the position of the cooler first stage. The maximum magnetic field at the top of the HTS leads is 0.33 T. With the magnetic field at the leads at that level, the field at the cooler motor is 0.22 T. The rotary valve and it motor can be shielded at this field level.

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